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Structural Flexibility and Its Impact on Contemporary Architecture

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Abstract. The concepts of structural flexibility became one of the important goals in the design phases to reach high performance in architecture. The pioneering projects and ideas that linked architecture with technologies and scientific innovations appeared, with the aim of reaching projects that mix the concepts of flexibility with the development of machine thought and modern technology to meet the functional, environmental, and aesthetic requirements for human wellbeing. The aim of this paper is to identify the mechanisms used in order to reach flexible structural systems capable of accommodating technological changes and developments. The research hypothesizes that the structural design according to the concepts of flexibility achieves high structural performance. The paper depends in its theoretical framework on a set of research and studies on the basic concepts of flexibility, and the possibility of their application within the structural design at the intellectual and application levels. The research methodology is based on identifying strategies and mechanisms to achieve structural flexibility, and then testing their compatibility with the established principles to reach high-performance structures**.**
The research concluded that the structural flexibility in contemporary architecture, especially those with technological innovation, has an active role in enhancing the structural performance of the building.
Keywords: Flexibility, Structural flexibility, Structural design, Structural efficiency, Architectural form, Material.

INTRODUCTION

Flexibility is generally a reflection of a system's ability to change or react without losing time, effort, cost, or performance, [1]. Hence, flexibility is a proactive feature designed in the system architecture, rather than a reactive behaviour that may lead to lose time, effort, cost and performance.

The term "flexibility" entered the architectural terminology in the early 1950s. Walter Gropius made one of the earliest assumptions of flexibility in 1954.

"The architects have to conceive building not as a monument, but as a receptacle for the flow of the life which they are to serve, and, that his conception should be flexible enough to create a background fit to absorb the dynamic features of our modern life". [2].

The concept of flexibility in contemporary architecture has become an approved approach within the design decisions that accompany all design stages, and for several aspects, most notably the functional aspect, including the structural part. The structural flexibility, which combines the concepts of adaptability, mobility and transformability and convertibility, is a goal to achieve a range of dynamism for the system and on more than one level - the level of the general form, the nature of the structural elements of the system, the nature of the joints within the components

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of the system, the level of the material and activating its role within the system - to achieve efficiency on one hand, and to provide the ability to control potential future changes on the other hand, in addition to the expressive aesthetic values added to the shape.

FLEXIBILITY AND ARCHITECTURE

Architect Yona Friedman linked the concept of flexibility in architecture with the concept of mobility, included in his article "Mobile Architecture" published in 1985. He considered flexibility a key concept in architecture and proposed a new type of mobility, which he called "General theory of mobility".[2] His concept of “Mobile architecture” did not mean mobility as much as giving dynamism to the adopted system in a way that allows adaptation to the variables while giving the occupants the freedom that enables them to use the building in the best way.

Flexibility is the first level in adaptive architecture, with a flexible structure realizing the possibility of making modifications to the building components. This ability is controlled directly by the user, which means that the component does not have the ability to change itself, thereby the components of the building are subject to change by an external force, and thus the different possibilities of change are limited. Whereas, flexible adaptation requires mechanical techniques for developing flexible systems, such as moving joints, sliding mechanisms, etc. [3]. The ability to adapt is classified as the ability and flexibility to achieve high performance efficiency. Or it is the ability to accommodate different social uses, so flexibility is the ability to accommodate various physical changes. Thus, the concept of adaptation is linked to work and use. And the concept of structural flexibility is related to physical changes, which are classified into three aspects [4]:

- Changes in the loads imposed on the structural system of the building.
- Changes in environmental forces.
- Changes in occupations as a result of job changes.

Flexible buildings are defined as “Buildings that are designed to allow for internal re-arrangement to suit the changing needs of occupants”. Adaptive buildings are “Buildings that are designed, implemented and maintained within the limits of addition or deletion in order to prolong their life and are compatible with new uses”. [4]. Accordingly, a set of design rules concerned with achieving flexibility and adaptability have been identified as follows [5]:

- Accuracy in designing structural joints and connection points between building systems.
- Use of prefabricated components and repeatable ingredients.
- Adopting modular systems to ensure compatibility with building components and elements.
- Adoption of replaceable and reusable components and elements.
- Use of construction materials that are recyclable.

Accordingly, the structural flexibility includes several concepts that fall within its available capabilities and are the basis for its realization, as follows:

- Adaptability: The ability of the built environment to accommodate multiple functions without fundamental change in the architectural structure.
- Mobility and Transformability: it is usually dealt with new external conditions such as a climate situation or a temporary emergency event. It is one of the solutions to achieve a state of adaptation, and allow for a wide range of change.
- Convertibility: The concept reflects a wide range of transformations and changes as it is used in structures that need to accommodate changing functions over time, and then the need to reduce construction costs and time by anticipating potential future needs.

In order to reach the required level of flexibility, the aforementioned capabilities must be incorporated into the design of the building in the early planning stages of the project, as early decisions lead to lower costs, ease of implementation, and the addition of capabilities with a greater positive impact. The application of structural flexibility ensures the dynamics of the system in order to control potential future changes - changes in the function of space, changes in the loads imposed on the constructive system of the building, and changes in occupancy capacity - as flexibility provides the ability to control the building for the entire building life cycle as well as the construction phase.

STRUCTURAL PERFORMANCE

The structure is described as the part of a building whose primary function is to provide the strength and rigidity necessary to prevent the building from collapsing. The structure may divide itself into two parts, a main part and a secondary part, and the nature of the relationship between them is determined by several design and functional specifications. The level of complexity within this structure varies depending on the level of connection between the main and secondary structure on the one hand, and between the structural elements and spatial elements on the other hand. Connectivity levels have a significant effect on the performance of structure in accordance with the characteristics or essential qualities, which are as follows [6]:

First: The state of equilibrium: It is imperative for the structures to be able to achieve the state of equilibrium - in various circumstances - within the framework of the act of over loads This necessitates dealing with the structure in a manner that ensures its ability to withstand and adapt to the surrounding changes, whether side loads or unexpected environmental impacts.

Second: Geometric stability: It is the property that maintains the geometry of the structure, and allows its elements to work together to resist the load. One of the basic requirements for Geometric stability is the ability of the elements to resist orthogonal loads, and at the same time work to organize the elements in a way that gives them the ability to achieve a state of balance in response to the forces that are exposed to it from three perpendicular directions.

Third: Strength and rigidity: The load imposed on the structure generates internal forces within the elements, and the external reaction force is within the foundations. The elements and foundations must have sufficient strength and rigidity to resist these forces, without failure in the materials and without potential deflection for it in the case of extreme loads.

STRUCTURAL DESIGN

The structural design process includes obtaining the optimal solutions resulting from the structural operational methods, and the decisions that accompany the early stages of the design process have a great impact on the final efficiency. The goal of reaching optimization is a clear goal for any design task, and it needs knowledge and tools occasionally. In some cases, finding the optimal solution may require additional costs in addition to modern technologies. In order to develop a clear methodology for the structural design process, it is necessary to define the stages that it passes through, and to know the limits of each stage and its importance in the overall design phases. The goal is to improve the form “Topology Optimization” that governs the general composition of the structural form, including the method of linking the structural elements and selecting the appropriate materials, see Fig. 1. In this context, the concept of structural morphology appears, which is concerned with studying the functional requirements of the structure in order to determine the properties and shape of the structural system, and is based on the sciences of mathematics, engineering and topology. [7]

According to the processes of structural morphology, the material, system, shape, properties, main and secondary components carrying loads are determined. Physical modelling, engineering and equilibrium calculations assist in crystallizing the form finding operations. Usually, the development in the methodology used in the conceptual design stage of the structure leads to the emergence of morphological indicators that reflect the approach used during that design stage, and determine in one way or another the mechanical behaviour of the approved structural system and the type of materials used, while meeting the basic criteria including strength, rigidity and stability, and its effect on the structural performance of the system. [7]. One of the ways to reach a high structural performance in the structural design as a whole, is to define the general orientation, and then discuss the typical stages of the design process, with the implications of levels of flexibility within the design. Accordingly, the research finds that the processes of structural design and selection of the optimal form go through several stages and at all levels - the general shape level, the detailed level and the nanoparticle level - and these stages are described as follows:

1. The conceptual design stage: It is the stage of arriving at the basic concepts upon which the form is built, and it differs in the scale with which it begins according to the chosen orientation. The sources of these concepts often depend on inspiration from nature and within the two scales, the general scale of shape, and the micro-scale at the level of the molecular composition of the materials of living organisms. The other source is physics and mathematics, with the help of progress in computer software.
2. The stage of translating the main concepts and ideas and within different levels of the basic structure of the system, which differs according to several factors, including functional, technical or aesthetic - in addition to the economic factor - in order to reach a state of balance called for by optimal design.
3. The detail stage that may extend to the implementation process, and the technical aspects, both the visible side - research and scientific knowledge - and the invisible side play a major role in the implementation process and designing the details.

In each of these stages the material used plays a prominent role in translating these concepts to finally come up with the approved form. Accordingly, achieving a stable balance is a major goal in the structural design, and it depends to a large extent on the engineering configuration of the structure, so the chosen form is one of the important criteria for evaluating the level of structural performance. And then the method of dealing with approved treatments for the structural elements that make up the shape and the sizes of the cross sections, and the nature of the joints adopted to connect the structural components so that the required strength and rigidity levels can be maintained.

To reach the optimum size by controlling the size of the cross section of a structural element such as bridges and columns, or by controlling the thickness of the panels and slabs. And access to the better shape “shape optimization” by controlling the location of the joints or nodes and controlling the surfaces that determine the structural shape. Then improving the shape “Topology Optimization” by controlling the general composition of the structural form and the method of linking the structural elements and selecting the appropriate materials. [8]

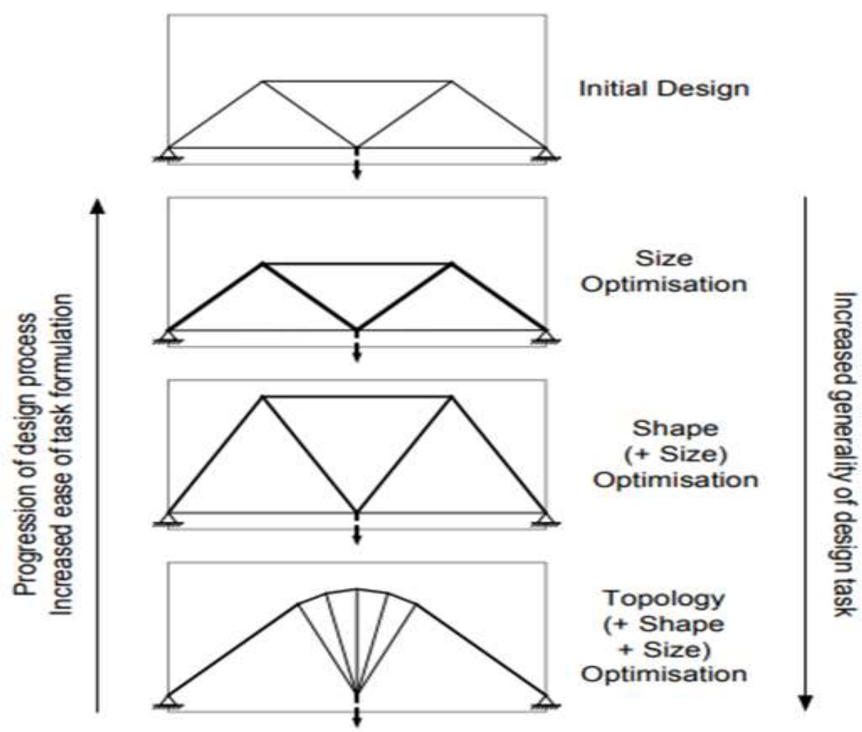

FIGURE 1. The initial design phase.

STRUCTURAL FLEXIBILITY

Achieving the concept of structural flexibility goes beyond several aspects of architecture, most notably the functional aspect, including the structural part. And it has become one of the prominent and fundamental goals of contemporary architecture. Over the course of the historical development of architecture, the dynamic ideas of architects and designers were feeding this concept, and it seemed to be clearly evident within the structural systems, starting from the concepts inherent in the conceptual design to the stage of translating those concepts and ideas, and within different levels of the structural system and at different scales.

The concepts of structural flexibility are embodied in the design decision of the structural system in accordance with three basic principles in order to reach the required structural performance, as follows [9]:

The first principle: compliance with the impact of potential loads.

This principle works in harmony with free forming and smoothing surfaces. It can be translated in three basic ways:

- Reduce Surface Loads - Change the shape to reduce the area affected by the loads.
- Reduce the morphological action - changing the shape to conform to the aerodynamics.
- Reduce Friction - Change the surface texture to increase smoothness.

The second principle: improving materials efficiency.

This principle emphasizes the importance of employing materials with shape in an integrated manner to resist the impact loads and improve structural efficiency, and this is done by:

- Activating the role of structural material - activation is done by reforming it.
- Material composition (composition and internal organization of material at the molecular level) - with the aim of changing the type and flow of internal forces.

The third principle: the timely distribution of the acting loads

It includes the distribution of the energy of an impulse loading so that the maximum value affecting the structure decreases. It is done by introducing dynamic concepts of forces to activate the load distribution process over a period of time. By adopting a secondary structure that is lightweight relative to the main one, and the secondary structure is based on the main one by means of a damper system.

Membrane structures, pneumatic structures, and three-dimensional cable net structures are characterized by structural flexibility that they derive from their structural elements and the method of linking those elements, which activates the process of balancing forces to reach the desired level of stability and balance. The structural system is usually applied to a main structure and a secondary structure, where the separation allows from the structural point of view to use secondary structures for the lightweight façade that has the possibility of free formation of the building envelope that is effective under different loading patterns, see Fig. 2. Where the system divides into a solid part that represents the main structure and usually consists of rigid materials of relatively high strength, and the flexible part represents the secondary structure and consists of relatively light flexible materials. This achieves one of the most important principles of structural flexibility, which is in compliance with the impact of loads. This mechanism is evident in multi-storey buildings, where the flexible part that represents the secondary structure absorbs wind energy.

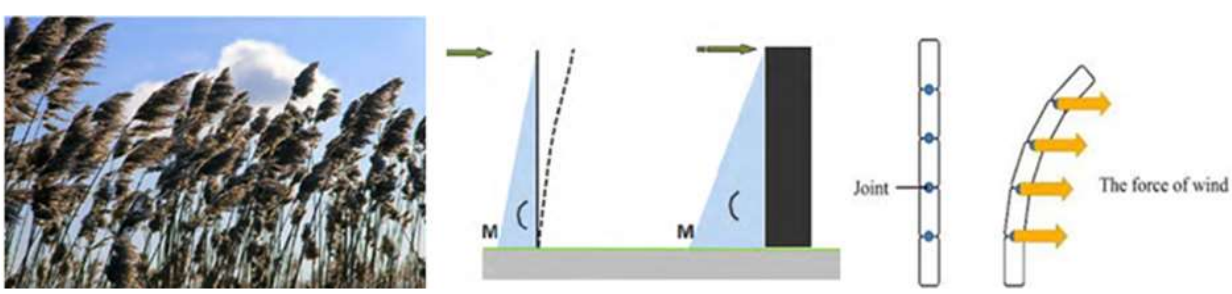

FIGURE 2. The Flexible behaviour towards wind forces due to the structure of the plant.

The structural flexibility is thus reflected through two main features that reflect the most prominent concepts of structural efficiency:

- Ensure that forces are transmitted by axial forces, resulting in higher efficiency and less material use.
- The possibility of absorbing forces in a dynamic way, which leads to a decrease in the internal forces and thus less use of materials.

as it consists of the solid part that represents the stem, and the flexible part represented by the branches and leaves. Nature of the joints between the parts of the structure provides a dynamic behaviour that distributes forces and resists lateral loads.

Accordingly, a set of criteria can be drawn up that can be adopted as indicators to assess the level of the building's structural performance, as shown in Table 1.

TABLE 1. Theoretical Framework: The vocabulary and indicators adopted in evaluating the level of structural performance of the building.

Indicators of assessing the level of the building's structural performance .	The state of equilibrium and Geometric stability	General form of the system.	The shape conforms to aerodynamics and ensures a homogeneous distribution of forces.
			Reducing the area affected by the loads and ensuring direct paths of the forces generated within the parts of the system.
		The nature of the structural elements of the system.	Choosing a form that ensures obtaining the shortest path of the forces generated within the parts of the system.
		The nature of the joints within the components of the system.	Selection of flexible joints for parts of the system that provide the necessary dynamic movement to absorb the energy of the impulse loads, and ensure that it is reduced to a minimum.
	Strength and rigidity	Type of material used.	The use of solid materials within the main structure and flexible materials within the secondary structure.
		Activating the role of the structural material	Activate the method of material formation, composition and internal organization of material to ensure direct and short paths of force flow.

THE CASE STUDIES

The research relied on the applied side on the analytical descriptive methodology for three case studies, according to the indicators that the research came out with, to assess the structural performance of the building, in order to verify the research hypothesis. and as shown in Table 2. The case studies were selected according to clear principles that have been extracted from the content of the research to achieve its objectives, which are:

- The structural system has one or more dimensions of structural flexibility.
- The case studies emphasize one or more of the indicators covered by the research.
- They have distinctive intellectual, and formal characteristics and is one of the prominent products in contemporary architecture.

The First Case Study: The New Beijing Poly Plaza in China

The New Beijing Poly Plaza in China designed by Skidmore, Owings & Merrill (SOM). The building was opened in 2007, see Fig. 3. The building is located in an area of seismic activity. It consists of 24 floors, multi-use containing shops, offices, restaurants, and a suspended museum which occupies eight floors. The eight-storey museum is suspended by diagonal cables made of cast iron. The building contains the largest glass wall in the world supported by a network of cantilever elements. This wall moves flexible movement as a result of wind loads. [10].

The structural system used with the added elements provides the ability to deal with seismic forces, by integrating the concepts of flexibility at different levels, starting from the tension system integrated within the secondary structure of the facades, to the type of flexible joints used between the parts of the system, which gives the required dynamism to absorb the generated impulse force.

Designing the structural system in a way that complies with the seismic loads and absorbs the generated kinetic energy, through the mobility and flexibility provided by the giant joints that work on the principle of pulleys and inspired by the movement of the arms and the axial movements of the shoulder joint - simulating the life systems - and the supporting grid of the glass wall is linked to the tensile forces of the two-way cable systems to absorb the lateral loads of the winds.[10].

Which was designed as one of the proposals to solve the problem of noise produced by airplanes in the Netherlands in 2008 see Fig. 4, using an active form that ensures a clear path of forces, as well as the flexible materials to avoid impact of lateral loads as well as sound absorption and a means of storing and transmitting solar energy. It works as an air sound barrier.[11].

The third case study: Cultural Center in Azerbaijan (Heyder Aliyev Center)

Cultural Center in Azerbaijan (Heyder Aliyev Center), designed by Zaha Hadid. The center was opened in2013, see Fig. 5. It is the primary building for the nation's cultural programs. It contains a museum, exhibition halls and a conference center. The most prominent challenges that faced the project's engineers in designing the

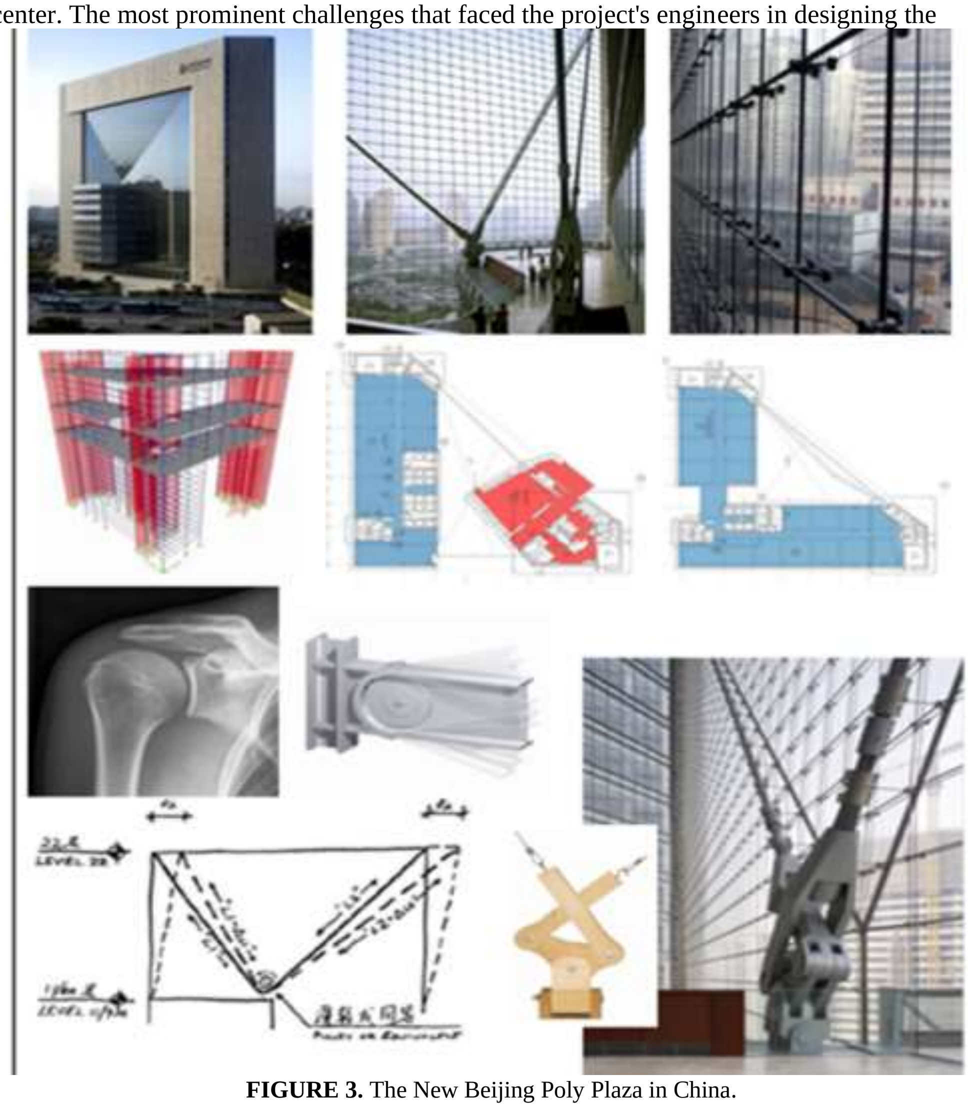

FIGURE 3. The New Beijing Poly Plaza in China.

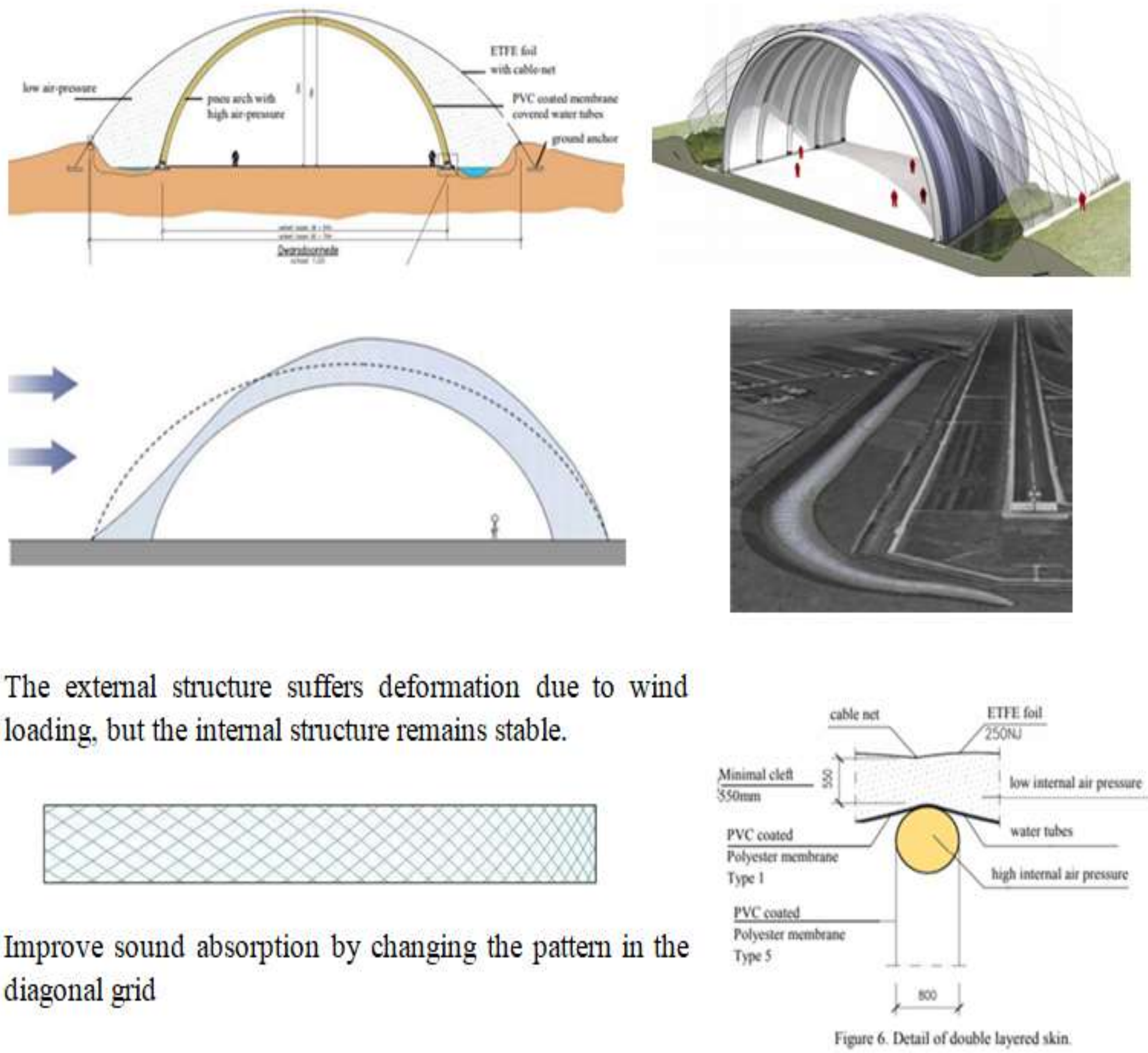

FIGURE 4. The structure of "Pneumatic Sound Barrier".

building, are the city being under strong wind loads throughout the year, as well as being within a seismic zone. The free shape of the structure aims to create a flexible streamlined surface to meet various functional requirements. One of the functional aims of the building is to create large, column-free spaces, giving visitors an opportunity for smooth movement inside.[12]. Heydar Aliyev Center shown in Fig. 5 consists of two structural systems: an external structure with a three-dimensional network of steel, and a concrete structure. The structure of the building allows to create a flexible relationship between the solid structural part and the outer shell that represents the outer shell of the building to create the free form of the surface, while adding the expressive side of the building.

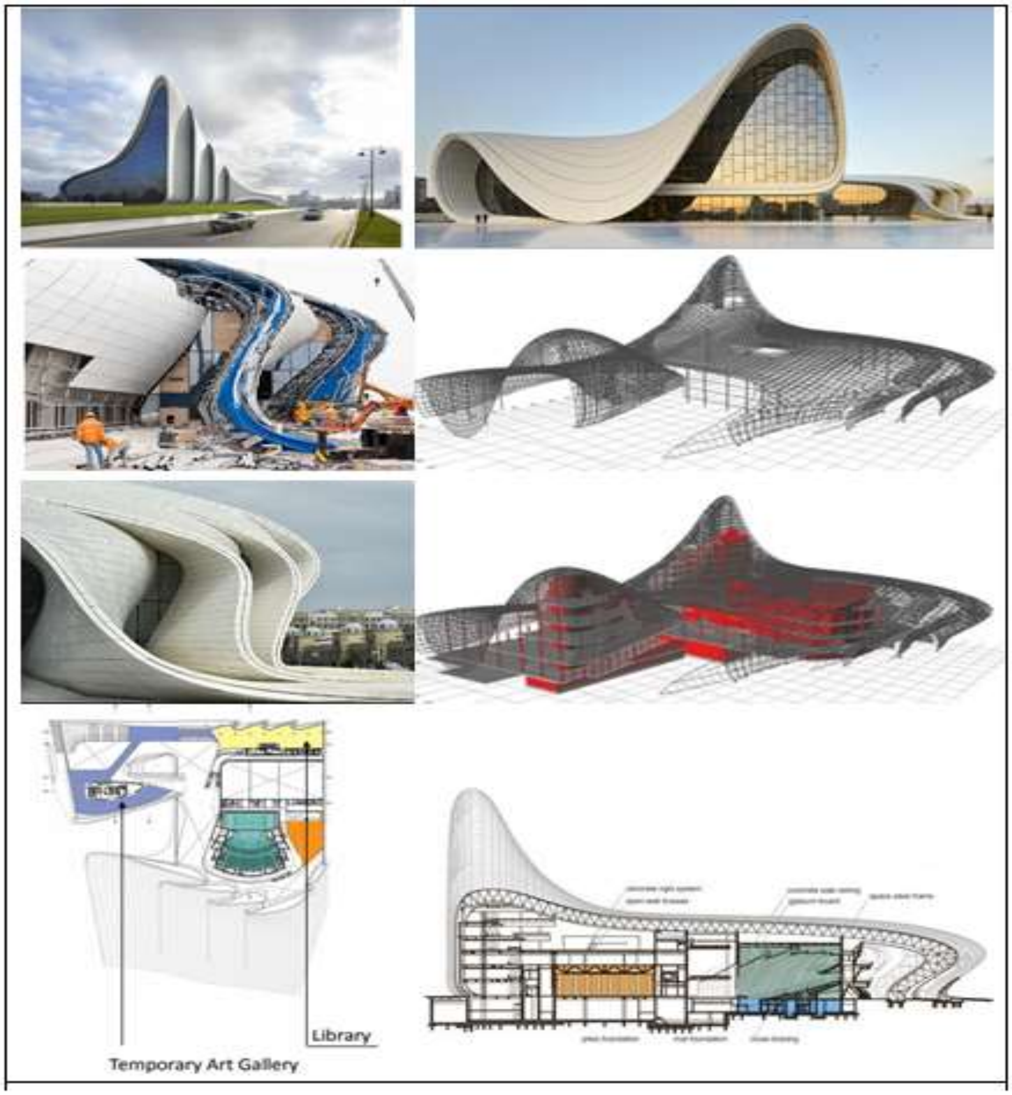

FIGURE 5. Heydar Aliyev Center

The building creates a continuous relationship between the surrounding square and the internal spaces of the building. This relationship was achieved by using a structural system consisting of two parts, one of which supports the other: Integrated concrete structure with a space frame system. The concepts of flexibility in the free formation of the building are used in activating the process of distributing the lateral loads of the building according to the principle of compliance with the impact of the loads.[12].

Accordingly, Table 2. extracts the characteristics of the selected case studies according to the basic vocabulary and their indicators that the research came out with within the theoretical framework in Table1, to assess the level of structural performance.

As a result of the analytical study of the selected study cases, and according to the vocabulary and indicators that the research came out with to assess the level of structural performance, and according to what is shown in Table No.2. We can conclude the following:

TABLE 2. Extraction of the selected case studies' characteristics

Selected Case study	Vocabulary and indicators for assessing the structural performance of the building.	
	The state of equilibrium and Geometric stability	Strength and rigidity
	General form of the system. - The nature of the structural elements of the system. - The nature of the joints within the components of the system.	Type of material used. - Activating the role of the structural material
The New Beijing Poly Plaza in China	-The design of the structural system is based on the principle of compliance with seismic loads and absorption of the generated pulsed kinetic energy. It consists of a primary structural system of concrete, and a secondary structural system of stainless steel. -The support network of the glass wall is linked to the tensile forces of the cantilever elements, which move a flexible movement to absorb the lateral loads of the wind. The principle is inspired by the flexibility that characterizes the movement of spider web when exposed to lateral loads. As well as the flexible joints used within the glass facade. -The use of diagonal cables for suspending the eight-story museum. Availability of giant joints - which works on the principle of pulleys and is inspired by the movement of the arms and the axial movements of the shoulder joint - the mobility flexibility needed to resist shear forces resulting from earthquakes.	− The system is made of a mixture of reinforced concrete and stainless steel. − The main structural system consists of three pillars of reinforced concrete, located at the corners supporting the horizontal floors of the building. − The use of stainless steel in the suspension system and in the main structure of the façades, as well as the steel hinges, that are essential elements for support and compliance with Lateral loads. − Support fittings from double high-strength stainless steel.
The structure (Pneumatic Sound Barrier)	-The structure system has an effective form that ensures a clear path of forces, while adopting the elastic material for the external structure to comply with the lateral loads and increase the structural efficiency. -The independent behavior of the external structure from the interior and the movement of air between the outer and inner envelopes result in a variable external load that has a limited effect on the internal structure. Therefore, the air arches that support the inner shell are often loaded with equal and permanent load resulting from the self-weight, water pipes and air pressure between the two casings.	− The external structure is flexible and is able to meet the lateral loads due to the action of the wind in a dynamic way, allowing for a homogeneous distribution of forces, while the internal structure is static. − The inner wall consists of a polyester membrane coated with PVC for laying water pipes. The outer covering is made of transparent membrane called (ETFE), which has been reinforced with a cable net.
Cultural Center (Heyder Aliyev Center) in Azerbaijan	-The use of a structural system consisting of two systems, one of which supports the other: a concrete structure combined with a three-dimensional grid system. The concepts of flexibility in the free formation of the building are used in activating the process of distributing the lateral loads of the building according to the principle of compliance with the impact of the loads. -The external structure is supported by "boot columns" that extend from the ground -on the west side- with a curvature that helps support the outer shell while providing a smooth flow to the outer surface. From the east it is supported by dovetails, which gradually decrease in size. The steel structure is connected to certain joints with the concrete structure through the steel bridges extending from the core, and at other points it is directly related to the foundations, in order to maintain the stability of the structure.	− Reinforced concrete is used in the main structure, mainly to construct shear walls and to separate the main spaces of the building and support the "space frame" steel frame. Which represents the secondary structure.

The first case study: It was distinguished by employing the principles of structural flexibility to achieve equilibrium and geometric stability at the level of the structural elements and the way they are organized, and at the level of the joints within the components of the system, where the flexible joints were adopted for the secondary structure supports on one hand, and in the method of linking the components of the secondary structure on the other hand. As for the materials level, reinforced concrete material was adopted for the main structure, and stainless-steel material for the secondary structure to achieve the required strength and rigidity for the building, which showed a distinct effectiveness for the reality of the structural flexibility of the first project.

The second case study: The effective form of the structural system was employed to ensure a homogeneous distribution of loads and direct paths of forces. The principles of structural flexibility were embodied in the manner of dealing with materials and activating the role of modern materials in both the main and secondary structure, and in the way of dealing with flexible and solid materials in an integrated manner within the main source. This resulted in a secondary structure that is characterized by kinetic flexibility that has the ability to absorb the energy of lateral loads while preserving the shape of the structure and returning it to the basic shape with the demise of the acting forces, through which it was confirmed that the structural flexibility components were distinguished for the whole building.

The third case study: The use of structural flexibility principles appeared to achieve equilibrium and geometric stability by adopting the free formation of the structure. To comply with aerodynamics and achieve a homogeneous balance of loads according to the principle of compliance with the impact of loads. The mechanism of the formalization of the system of structure helped the existence of a primary and a secondary institution working to achieve this goal. And embodied the principles of structural flexibility in the manner of dealing with the points of support and the geometric formation of the columns for the supports of secondary structure. As for the materials, the reinforced concrete material for the main structure was adopted, and the steel “the space frame” to give the free formation of the secondary structure.

Based on that, the research confirmed his hypothesis that structural design according to the concepts of flexibility achieves high structural performance.

CONCLUSIONS

The structural flexibility in contemporary and technologically innovative architecture has become an approach that responds to the external and internal need for change and development, due to the constant forces of change in human life, as well as the desire for diversity and innovation. Where the forces of change affecting the human being are governed by two types of forces: external forces represented by environmental conditions on one hand, and internal inherent forces stemming from the human will to reach the optmal solutions on the other hand.

The most prominent mechanisms that are adopted, which have been extrapolated from experiences and projects designed according to the concepts of structural flexibility, can be summarized as:

- The use of the structural system of effective form and flexible material: flexible and lightweight materials are used in kinematic structures to achieve the required dynamic balance of the system.
- Scalability of the system and ensuring accessibility to the parts of the system: the division of the structural functions through an independent structure that protects the internal building, where the structural independence allows for a greater range of bends to the external surface, which increases the performance of the structure. It limits the lateral forces - the horizontal wind forces - and the unwanted acceleration these forces create.
- Standardization of the components of the system gives flexibility to the system by using it as a repetitive unit to achieve the free for of the structure in line with the aerodynamics to comply with the impact of the loads imposed on the structure on one hand, and the possibility of replacement and re-use ability on the other hand.

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